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DISCUSSION OF DESIGN OF LARGE COAL BUNKERS

(Published in June, 1951)

By George L. Blanchard, Alexander M. Turitzin, and Paul Rogers

STRUCTURAL DIVISION

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DISCUSSION

GEORGE L. BLANCHARD,[10] M. ASCE.—The first recent attempt to make available to the designer a modern and practical solution to the problem of coal bunker design is presented in this paper. The author refers to studies made in France and, in particular, uses one of the formulas proposed by M. Reimbert made to extend the cylindrical deep silos pressures equations to square or rectangular bunkers.

The writer wishes to emphasize the fact mentioned by Mr. Rogers that those studies,[11] which were originally based on experimental research, have proved that the exponential expression as used by Mr. Janssen was inadequate for the computation of pressures in the upper zones of a bin, and gave results far below those measured experimentally.[12] Mr. Albert Caquot,[13] through rather elaborate and complete mathematical developments, has evolved an original method and practical formulas, the results of which appear to corroborate closely those obtained with Mr. Reimbert's method. The writer has had the occasion to use both the Reimbert and Caquot methods in specific cases of design. It has been found that the percentage of discrepancies between the two was so small as to be unimportant. On the contrary, the use of the Janssen formulas has led, for example, to an underestimation of pressures and tangential forces at wall faces of more than 33% less at depths of 10 ft from the top to 10% less only at 80 ft down from the top.[14] According to reliable authorities, there lies the main reason for certain types of disorders observed in the upper zones of deep silos built in reinforced concrete. The paper deals with structural steel bunkers specifically. Therefore, the remarks may appear somewhat as a superfluous refinement, considering the arbitrary assumptions, with questionable degree of accuracy, which are often accepted as regards the characteristics of the material to be handled and the conditions of the wall's face. It is obvious, however, that an important underestimation of the lateral pressures and forces should be avoided consciously, particularly in the upper part of such a complex structure as a coal bunker of large capacity, where the solicitations of the structural elements are multiple and intense under constantly variable service conditions. The purpose of the present comment is to draw the attention on this particular point and bring up some additional precisions to the author's note.

The needs of more elaborate and precise methods of structural design cannot be emphasized too forcibly to prevent the temptation of the designer to com-

NOTE.—This paper by Paul Rogers was published in June, 1951, as *Proceedings-Separate No. 72*. The numbering of footnotes, equations, and illustrations in this Separate is a continuation of the consecutive numbering used in the original paper.

[10] Consulting Engr., Algiers, Chicago, Ill.

[11] "Recherches nouvelles sur les efforts exercés par les matières pulvérulentes ensilées sur les parois des silos," by M. Reimbert, *Annales de l'Institut Technique du Batiment et des Travaux Publics*, Paris, France, Série I, May, 1943, pp. 1–60.

[12] "Etude expérimentale et théorique des contraintes dans les Silos," by Maurice Buisson, *Travaux*, Paris, France, April, 1943, p. 129, August, 1943, p. 290.

[13] "Traité de la Mécanique des Sols," by Albert Caquot and R. Kérisel, Gauthier-Villars, Paris, France, 1949, Chapter VII ("Silos"), p. 350.

[14] Discussion by G. L. Blanchard of "Design of Hexagonal Bins," by Paul Rogers, *Journal*, A. C. I., December, 1950, Part 2, pp. 34–46.

pensate for the risk of uncertainties by an empirical and unjustified increase in the structural sizes or in the quantities of critical materials, particularly at the present time.

The author's paper, in that respect, is a valuable contribution to the improvement of methods of design accessible to a larger number of structural designers in the tremendously important field of power production.

ALEXANDER M. TURITZIN,[15] M. ASCE.—In addition to the statement (under the heading, "Coal Pressure") that—

> "The shallow bin theory is applicable to smaller bins where the plane of rupture does not intersect the opposite wall. For most large coal bunkers, however, the deep bin (or silo) theory is applicable."

the author should have given a definite criterion or a procedure to follow in determining the theory applicable to any bin size and shape.

After the capacity and the shape of the coal bunker is determined, the designer is confronted with the problem of determining whether he should follow the shallow bin theory or the deep bin theory to compute the pressures exerted by the coal on the bin walls. An analysis of the plane of rupture and the derivation of the criteria for both a shallow bin and a deep bin will indicate when to use one or the other of the two theories. It is generally conceded that when the plane of rupture intersects the surface of the coal, the bin is called a shallow bin. It is assumed that the mass of coal is unlimited, or at least of sufficient extent so that the outline of the sliding wedge (that is, a wedge having the wall as one side and the plane of rupture as the other side) is not interrupted.

The closer the walls, the more erroneous the shallow bin theory is; and when the walls are so close together that the plane of rupture does not intersect the surface of the coal but falls on the opposite wall, the weight of the coal is largely supported on the sides by friction. The deep bin theory must be used to deter-

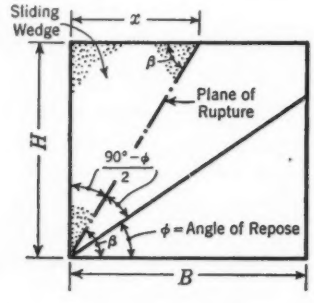


FIG. 10

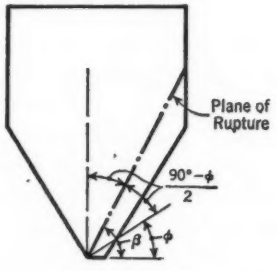


FIG. 11

mine the pressures exerted on the bin walls. According to the Coulomb theory, the plane of rupture lies between the angle of repose of the filling and the back of the wall. For a wall without surcharge (surface horizontal), the plane of rupture bisects the angle between the plane of repose and the back of the wall.

[15] Structual Engr., Devenco Inc., New York, N. Y.

Fig. 10 illustrates the relation between the angle of repose α, for such a case, and the angle β that determines the plane of rupture.

From the definition previously given, the criterion for a shallow bin is

$$x < B \quad \ldots\ldots (10)$$

From Fig. 10,

$$\tan \beta = \frac{H}{x} \quad \ldots\ldots (11)$$

Solving for x in Eq. 11 and substituting in Eq. 10,

$$\frac{H}{\tan \beta} < B \quad \ldots\ldots (12)$$

From Fig. 10,

$$\beta = \phi + \frac{90^\circ - \phi}{2.} = \frac{\phi}{2} + 45^\circ \quad \ldots\ldots (13)$$

Substituting the value of β from Eq. 13 into Eq. 12,

$$\frac{H}{\tan\left(\frac{\phi}{2} + 45^\circ\right)} < B \quad \ldots\ldots (14)$$

When the angle of repose ϕ of the coal is equal to 35°,

$$\frac{H}{\tan (62^\circ\ 30')} < B \quad \ldots\ldots (15)$$

and

$$\frac{H}{B} < 1.9 \quad \ldots\ldots (16)$$

Eq. 16 shows that when the ratio of the height to the width of a coal bin is less than 1.9, the coal bin is called a shallow bin and therefore a shallow bin formula should be used to determine the pressure.

For a hopper bin, a graphical solution is the most convenient. The procedure to follow in determining whether a coal bin is a shallow bin or a deep bin, with reference to Fig. 11, is as follows:

1. Draw a transverse cross section of a bin to any convenient scale.
2. From the lower left corner of the bin, plot with a protractor an angle of 62° 30′; the plane thus formed is the plane of rupture.
3. If the plane of rupture does not intersect the wall of the bin, the hopper bin is a shallow bin. A deep bin is shown in Fig. 11.

PAUL ROGERS,[16] M. ASCE.—The need for more accurate analysis in connection with the deep bin theory is emphasized by Mr. Blanchard, who refers to the works of the outstanding French engineers, M. Reimbert,[11] M. Buisson,[12] and A. Caquot and R. Kerisel.[13] It is true that the Janssen formulas had been developed for circular bins only, and their use, without corrections, for square and rectangular cross sections is definitely fallacious. This is not rec-

[16] Structural Design Engr., Sargent & Lundy, Chicago, Ill.

ognized easily, however, because, through a mathematical incongruity, the hydraulic radius of a square is identical with that of the inscribed circle.

With the advancement of science and the measuring technique, it should become obvious that Mr. Janssen's pioneering formulas are not entirely accurate. It is believed that the findings and advanced theories of the French scientists should be presented to the American engineers. This is a problem, however, in the realm of the engineering mechanics and cannot be included in the scope of a practical paper dealing with actual design.

Further experiments have been conducted by the Institut Technique du Batiment et des Travaux Publics, under the direction of Mr. Reimbert, with particular emphasis on dynamic and impact forces acting on the stored material in the bins. Much is to be learned yet about the internal stresses, especially in very deep bunkers where a 50-ft or 60-ft "head" may materially change the density of the coal. The density of "cyclone" boiler coal is considerably greater than the ordinary kind, probably because of the dust particles, and it is advisable to increase all tabulated values by 20% when such coal is used. Accurate information as to the value of the internal friction and the angle of friction between the coal and the wall should also be forthcoming. Mr. Turitzin emphasizes the necessity for a clear definition between the shallow and deep bins. His suggestions are practicable for bins with vertical walls and, in accordance with the classical theory of equivalent fluid pressure, for granular materials. However, the reduction of the coal pressure resulting from friction between the coal and the wall is applicable even for shallow bins.

The governing factor in the design of coal bunkers is not the coal pressure but the tendency of the bend line to straighten. This tendency is partly counteracted by the coal pressure. Thus the assumption of unreasonably large coal pressure may not produce a safe design because it may reduce the inward acting forces unrealistically.

The importance of these inward forces cannot be overemphasized. Not only does analysis show their existence, but also the measurements and visible movements of models and prototypes definitely prove their actions. Several cases are known whereby the opposite bend lines were connected by limber "ties," presumably to restrain outward forces only, to ensure that these members will fail in buckling. The distribution of the forces and moments in bunkers is not unlike inverted gable frames where the moments are produced by the deviation of the pressure line from the actual shape of the frame.

The foregoing discussion would imply that the ideal bunker is what is commonly known as the catenary or suspension bunker because, under ideal loading conditions, no moments are present—only pure tension in the bunker walls.

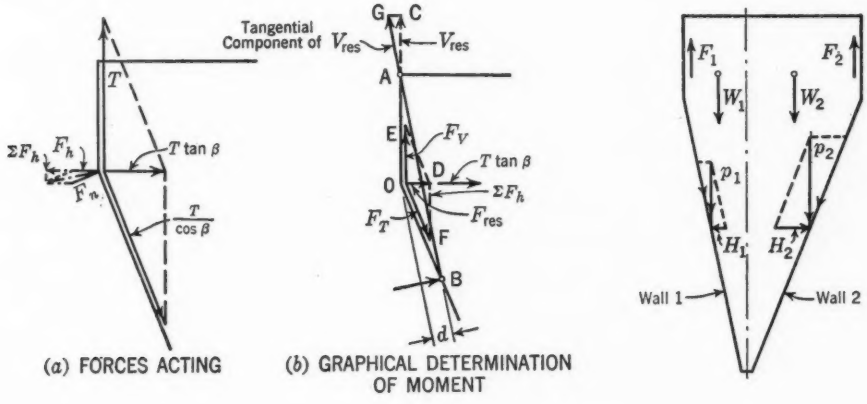
There are numerous objections to these catenary bunkers, however. There is no accurate theory giving the shape of the bunker. The commonly used triangular loading, as it is given in older textbooks, is definitely inadequate because it disregards the coal pressures. Should one attempt to obtain a reasonable funicular polygon, by a cut-and-try method, based both on vertical and horizontal forces, there still would be many uncertainties as to the value of such forces. Catenary bunkers are not self-cleaning and there is a constant danger of instanteneous combustion of the coal.

As the outlets must necessarily be about 12 ft to 16 ft apart, the coal must be directed toward these outlets by timber bulkheads or lean-mix concrete saddles. A large part of the capacity is thus lost, and the bunker is considerably stiffened instead of being elastic. The fabrication is costly; the rolling of the steel plates and stiffeners to the exact catenary shape is quite difficult; and substitutions by circular arcs are faulty.

When catenary bunkers are loaded, the sides bulge outward and the bottom moves upward. Consequently, the outlet connections must be flexible to allow for these vertical movements, which may amount to several inches. Unsymmetrical cross sections are impossible with catenary bunkers, thus imposing a serious restriction on the layout.

The foregoing difficulties indicate that the disadvantages of the catenary bunkers far outweigh the advantages due to reduction of bending moments. Considerable savings can be achieved by proper layouts of regular bunkers composed of straight sides. If the side walls are on a column-row, such walls also act as deep girders between columns and there is no need for supporting beams. More than a dozen large bunkers (up to 2800 ton capacity) have been designed and built based on the principles expressed in the paper, and all of them were operating very successfully in 1952.

Corrections for Transactions.—In Fig. 4, change w to W; in footnote 4, "Engineering News" to "Engineering News Publishing Company"; in the title of Table 3, "Equation 8" to "Equations 8"; on page 10, line 7, "plus F_n" to "plus F_h"; in footnote 8 "parios" to "parois"; and corrected Figs. 6 and 7 as follows:



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